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Warm high velocity CO in the wind of Sakurai's Object (= V4334 Sgr)

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ABSTRACT
We present UKIRT UIST spectra of Sakurai's Object (=V4334 Sgr) showing CO fundamental band absorption features around 4.7 μm. The line-centres are at heliocentric radial velocity of -170 ± 30 km s^{-1}. The number and relative strengths of the lines indicate a CO gas temperature of 400 ± 100 K and CO column density of $7^{+3}_{-2} \times 10^{17}$ cm^{-2}. The gas was moving away from the central star at an average speed of $\sim$290$\pm$30 km s^{-1} in 2003 September. The lines appeared sometime between mid 1999 (well after the opaque dust shell formed) and mid 2000 and may have been somewhat more blue–shifted initially than they are now. The observed CO velocity and temperature indicate the continued presence of a fast wind in the object, previously seen in the He I 1.083 μm line beginning just prior to massive dust formation, and more recently in atomic and ionized lines. The dust continuum is consistent with a temperature of 350$\pm$30 K, indicating continued cooling of the shell. The similar CO temperature suggests that the bulk of the CO absorption occurs just outside of the dust continuum surface.

Key words: stars: individual: V4334 Sgr – stars: individual: Sakurai's Object – circumstellar matter – infrared: stars

1 INTRODUCTION

Stellar evolution theory accounts reasonably well for the effects of thermal pulses on the development of stars on the Asymptotic Giant Branch. Less well constrained are the effects of a late thermal–pulse (LTP, once the star has shed its envelope) or very–late thermal–pulse (VLTP), once the star has begun to descend the white dwarf cooling track). However, indications are that perhaps 10 to 20% of low– and intermediate–mass stars undergo LTP or VLTP. It appears that the subsequent "born–again" evolution across the HR diagram is short lived (perhaps a few centuries, but perhaps as short as a few decades; see Iben, Kaler, Truran & Renzini 1983; Iben, Tutukov & Yungelson 1996; Lawlor & MacDonald 2003), and consequently very few are observable at any one time. Sakurai's Object (= V4334 Sgr) is probably the first example of a VLTP observable with non–optical instruments in the immediate post–flash epoch.

Sakurai's Object was first identified as possibly undergoing a helium–shell–flash on 1996 February 23 (Nakano & Sakurai 1996; Benetti, Duerbeck & Seitter 1996), but it is clear that it started to increase in brightness in mid–1994 (Takemizawa 1997). In 1995 we began an infrared (IR) spectroscopic monitoring programme using the United Kingdom Infrared Telescope (UKIRT) and the cooled grating spectrometer CGS4 (Mountain et al. 1990); more recently we have used the UKIRT Imaging Spectrometer UIST (Ramsay-Howat et al. 2000). Observations are carried out throughout the star's observable period each year and the latest data, taken in 2003 September, are presented here.

2 OBSERVATIONS

Spectra of Sakurai's Object covering 1.4–5.3μm were obtained at the United Kingdom 3.8 m Infrared Telescope on Mauna Kea on 2003 September 8 (UT), using the facility's imager/spectrometer UIST. The instrument was configured with a 0.48″ slit, providing resolving powers of approximately 500 (600 km s^{-1}) at 1.5–2.5μm, 1400 (214 km s^{-1}) at 2.9–4.1μm, and 1200 (250 km s^{-1}) at 4.5–5.2μm. Spectra of early type stars were obtained in order to correct

for atmospheric transmission and provide approximate flux-calibration. Where possible, hydrogen recombination lines in the calibration stars were artificially removed prior to ratioing. This correction was not done at some wavelengths due to the contamination of the hydrogen line profiles with strong telluric features. A Gaussian smoothing with FWHM of 1.5 pixels was applied to the resultant spectra, degrading the resolving powers by $\sim$7% from those given above. Wavelength calibration in the M band was derived from a quadratic fit to telluric absorption features and has a $\pm 3\sigma$ accuracy of $\pm 0.0004\mu$m (25 km s^{-1}).

3 RESULTS

The overall 1 to 5 μm spectrum in 2003 September remains dominated by the dust continuum, as it had since 1999. Comparison with the 1-5um spectrum obtained in 2002 July shows that the dust has continued to cool (Tyne et al, in preparation).

The central result of this paper is the detection of fundamental vibration–rotation CO band lines around 4.7 μm in 2003 September. These are clearly visible in Fig. 2, and show a heliocentric average velocity–shift of -170 ± 30 km s^{-1}. Essentially all the fundamental P–branch lines from $J = 3$ to $J = 18$ are present (J is the rotational quantum number of the absorbing level). The spectral interval corresponding to the lower end of the P branch has been removed due to the interference of blended telluric and stellar absorption features. Similarly we see the R–branch features from $J = 2$ to 20 (with $J = 0$ and 1 again lost due to the calibration star features). The CO lines are unresolved in the spectrum and therefore are narrower than about 200 km s^{-1} (FWHM).

Marginal evidence is present for detection of the ^{13}CO fundamental, whose band center is 4.77μm and whose line wavelengths beat with those of ^{12}CO. The strongest modulation in the spectrum is near 4.75μm, corresponding to the wavelength of strong ^{12}CO and ^{13}CO lines. The small variation in the modulation is consistent with a ^{12}C/^{13}C ratio no less than 3 (in agreement with the recent determination of 4$\pm$1 by Pavlenko et al. (2004)) and we can rule out the lower half of the range of values (1.5 – 5) suggested by Asplund et al. (1997, 1999). Since the ^{12}CO lines are not heavily saturated (otherwise the ^{13}CO lines would have a more pronouced effect on the spectrum), the FWHM's of the CO lines must be no less than $\sim$25 km s^{-1}.

We have re–examined spectra of Sakurai's Object dating back to 1999. We find that the CO lines are present but less prominent in the 2002 and 2000 spectra (due largely to the lower resolution, see Tyne et al. 2002, for a discussion of the earlier spectra), but noisiness of the data makes this uncertain in the 2001 and most of the 1999 spectra. However a single M–band spectrum on 1999 May 4 (covering only the region 4.588–4.748 μm) shows that the R(1) to R(7) and the P(1) to P(9) lines are certainly absent. Thus we can constrain the appearance of these lines to after 1999 May 4, and state with certainty that they were present by 2000 April 17. We infer that the CO features appear to have been present for all but the early stages of the current deep dust–induced optical dip.

The heliocentric radial velocity of Sakurai's Object is 115 km s^{-1} (Duerbeck & Benetti 1996). Thus the observed CO is moving away from the star at around 290$\pm$30 km s^{-1}. The earlier data from 2000 April 17 are consistent with a velocity relative to the star of 360$\pm$60 km s^{-1}, where the higher uncertainty is due to the lower resolution and poorer signal–to–noise ratio. The difference between the two values is not significant within the uncertainties.

Although we have shown that the ^{12}CO lines are not heavily saturated, their roughly comparable line strengths between $J = 4$ and $J = 15$ are incompatible with optically thin lines existing within a small range of temperatures. Because of this and the low spectral resolution, the observed spectrum is not amenable to simple modeling in order to obtain accurate values of temperature and column density. However, crude estimates can be made as follows. Beyond 4.81 μm the spectrum is strongly affected by telluric absorption lines at many wavelengths. The P(16) line is blocked from view. P(17) and P(18) are clearly present, but the P(19) and higher lines are absent. If the CO temperature were higher than $\sim$500 K, the line intensities should not drop off very rapidly beyond 4.83 μm and there is no reason why we should not see more lines than we do. A temperature less than about 300 K would lead to very saturated low excitation lines. However the low J lines close to the band centre (4.67μm) are clearly weaker than the higher J lines. Thus we conclude that the CO temperature is between 300 and 500 K, and adopt a value of 400$\pm$100 K. Our preliminary estimate the dust temperature, based on the 1–5 μm spectrum (Fig. 1) is 350$\pm$30 K. This is consistent with the temperature of the CO and suggests that the CO and the dust are at a similar distance from Sakurai's Object.

For the case of a P-branch CO fundamental band absorption line from the ground vibrational state, the equation for the optical depth of a Gaussian vibration-rotation line, given by Geballe et al. (1972) can be simplified and transformed into the following expression for the column density of CO:

$$N(\mathrm{CO}) \;\approx\; 2.9 \times 10^{14}\ \frac{\tau\ T\ \Delta v}{J}\ e^{E/kT}\ \mathrm{cm}^{-2} \qquad (1)$$

where T is the temperature of the CO, τ is the optical depth, Δv is the full width at half maximum in km s^{-1}, J and E the rotational quantum number and the energy above ground of the absorbing level respectively. Using this we estimate the column density of CO to be $N = 7^{+3}_{-2} \times 10^{17}$ cm^{-2}, where the lower value corresponds to the higher temperature. Here we have used the (unresolved) P(15) line and assumed that it is optically thin so that the product of the central optical depth and linewidth is constant at a fixed value of N. If this assumption is incorrect or if there is a significant column of cold CO (not well seen in these data), the column density could be considerably larger.

4 DISCUSSION

4.1 The origin of the CO

There are several possible origins for the newly–discovered CO features. We address each in turn.

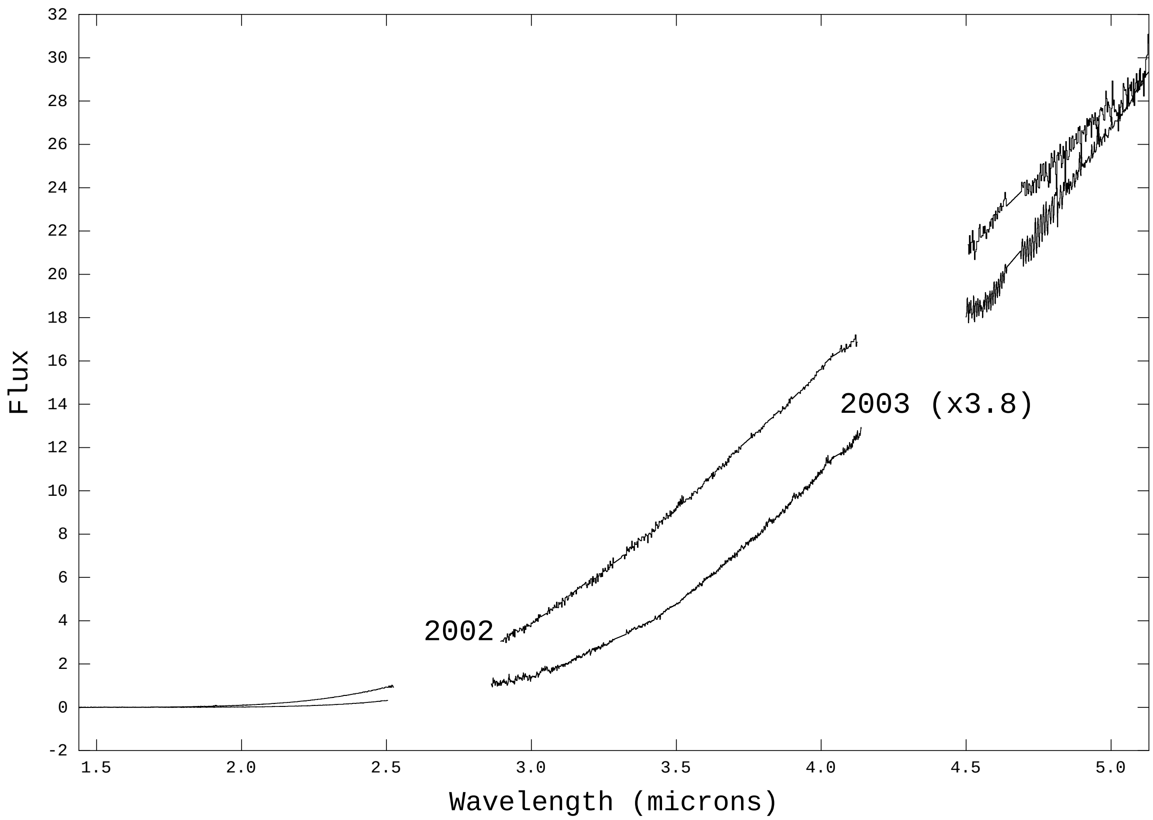

Figure 1. UKIRT spectra from 2002 July 11 (upper line, Tyne et al. in preparation) and 2003 September 8 (lower line). The latter has been scaled by a factor 3.8 in flux to aid comparison of the continuum form. Flux units are 10^{-13} Wm^{-2} μm^{-1}. The gaps are due to gaps in the wavelength coverage.

4.1.1 Interstellar CO

The CO may be in the interstellar medium in the direction of Sakurai's Object. We can immediately rule this out. Interstellar CO should have been visible with the same column all along (i.e. in the 1999 May spectrum). The number and relative strengths of the lines (see § 3 above) indicates that the CO is too warm to be interstellar. Finally the radial velocity suggests the CO is associated with outflow from Sakurai's Object.

4.1.2 Recently–formed CO

The CO may have formed further from the star than the dusty material shortly before detection (i.e. after 1999 May 4 but before 2000). However the carbon–rich nature of the dust (Tyne et al. 2002) suggests there is little oxygen in the region currently occupied by the CO. In addition molecules must form before dust forms. It is more plausible that the CO formed first, within the region now dominated by dust. Thus this origin for the CO cannot be supported.

4.1.3 CO formed in the dense wind

Neither of the previous suggestions for the origin of the dust is tenable, and it appears most likely that the CO that is being observed formed close to or in the outer layers of the central star prior to 2000. In 1999 May the CO was not visible against the dust continuum, but shortly thereafter it became detectable. Modeling of the evolving dust continuum (Tyne et al, in preparation) suggests that the continuum surface is expanding at about 50 km s^{-1}. However, the dust grains themselves may be moving at much higher speed than this. The central object is probably continuing to generate a high speed wind which, once it cools, is likely to form both molecules and dust. Clearly considerable gas is now outside of the continuum surface and has been for some time (since 2000). An alternative model, which seems more contrived, is that the dust shell and high speed gas are separately produced entities and that the CO–containing gas overtook the dust shell some time after the star was obscured.

4.2 Fast wind

We find CO absorption features consistent with a wind moving at $\sim$300 km s^{-1}. Eyres et al. (1999) suggested a $\sim$670 km s^{-1} wind explained a broad P Cygni feature in helium at 1.083 μm, with the breadth of the line consistent

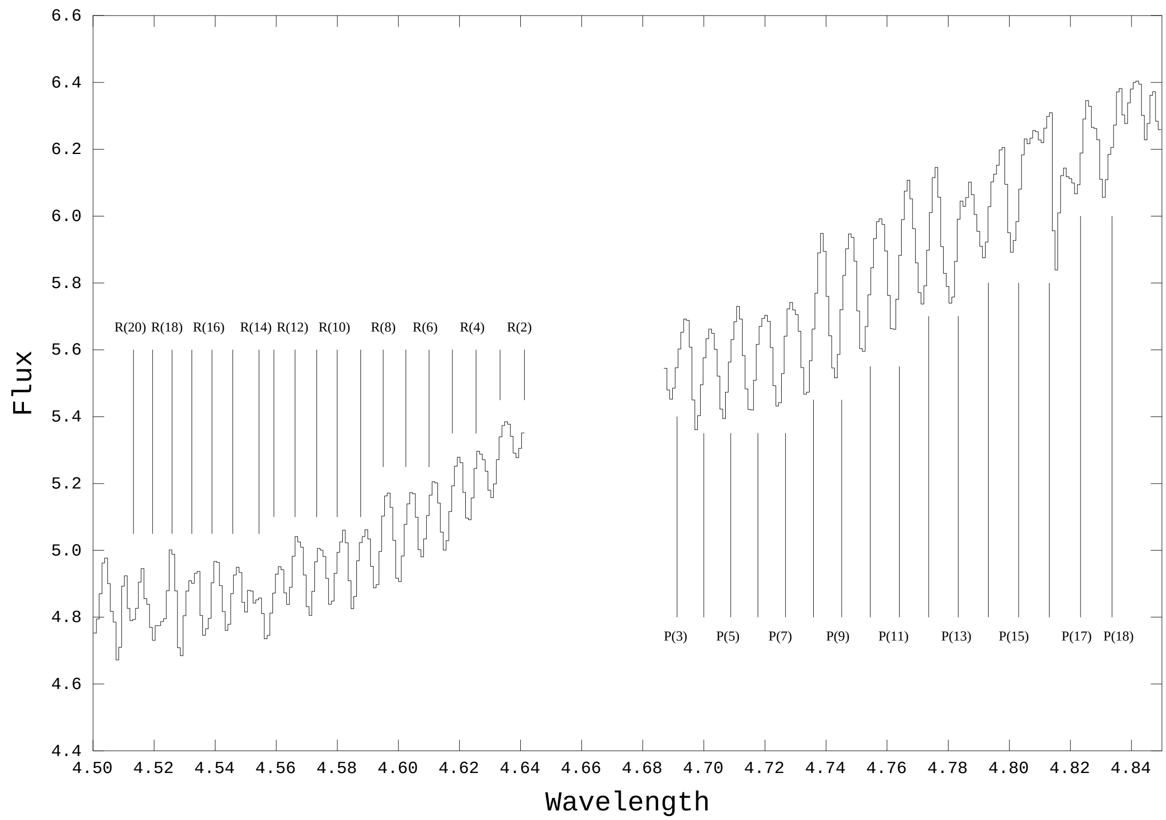

Figure 2. UKIRT UIST spectrum from 2003 September 8 in the wavelength range 4.45 to 4.95 μm . The CO fundamental band (1–0) lines are clearly apparent in absorption. The rest wavelengths for the R and P branch lines are marked by J–number. Flux units are 10^{-13} Wm^{-2} μm^{-1}. The gap at the centre of the wavelength range is due to the removal of telluric features.

with material moving at velocities down to $\sim$200 km s^{-1}. We believe this demonstrates that a fast wind continues to stream away from Sakurai's Object. The development of a fast wind following a VLTP and the subsequent heating up of the cental star is a prediction of the theory (Iben, Kaler, Truran & Renzini 1983). Kerber et al. (2002) suggest that the central star had entered this phase by 2001; we find that a fast wind has been in evidence since 1998.

5 CONCLUSION

A recent spectrum of Sakurai's Object has clearly revealed the presence of highly blue–shifted absorption lines of the fundamental band of CO. The CO was first noted in a spectrum from 2003 September 8. Re–examination of previous lower resolution spectra shows that the CO features must have arisen between 1999 May 4 and 2000 April 17. The blue–shift of the lines is consistent with gas moving away from the central star at $\sim$300 km s^{-1}. The number and relative strengths of the lines suggest a CO gas temperature of 400 ± 100 K and CO column density of $7^{+3}_{-2} \times 10^{17}$ cm^{-2} (the lower value corresponding to the higher temperature), and linewidths no greater than 25 km s^{-1} (FWHM). We rule out interstellar CO as the source of the absorption lines, but the circumstellar CO could be formed shortly before discovery or existed for some time prior to emerging from the dusty shroud. We note that the CO velocity is additional evidence for the existence of a fast wind in this object, although we cannot make a direct connection with changes in the central star. Taking the 1–5 μm spectrum overall we find that the dust continues to cool, and the temperatures of the CO–bearing and dust–bearing materials are similar. Hence the two components presumably lie at a similar distance from the central star. As the CO is moving more rapidly than the dust continuum surface, this suggests an ongoing wind replenishing the CO in the region of the dust.

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